Instability Issues at SNS Accumulator Ring

S.Y. Zhang
AGS Department, BNL

Workshop on Instabilities of High Intensity Hadron Beams in Rings
BNL, June 28 – July 1, 1999

SNS Storage Ring

Parameter		SNS	Unit
Beam Power	P	2	MW
Total Particle	N	2.08	10^{14}
Circumference	C	220	m
Kinetic Energy	E_k	1.0	GeV
Repetition Rate		60	Hz
Bunch Length	t_B	550	ns
Injection Turns		1200	
RF Voltage, $h = 1/2$	V_{RF}	40/20	KV
Beam Momemtum Spread	$\Delta p/p$	0.7	%
Beam Current	I_0/I_p	40/80	A
Ave. Chamber Radius	b	10	cm
Uncontr. Beam Loss		0.02	%
Beam Loss Power /m		1.8	W/m

- High intensity: Space charge, Particle distribution,
- High power: Beam loss, Activation, SNS power is 13 times higher than ISIS, 26 times for PSR.
- Activation is limiting the PSR at ~ 75 KW.
- SNS will have impact on the growing interest of very high power hadron beams.
- Large aperture: Impedance issues, Fringe fields, Large beam size,
- High RF voltage: Large beam momentum spread, Tolerance to longitudinal space charge effect,
- Selected issues of impedance and instabilities.

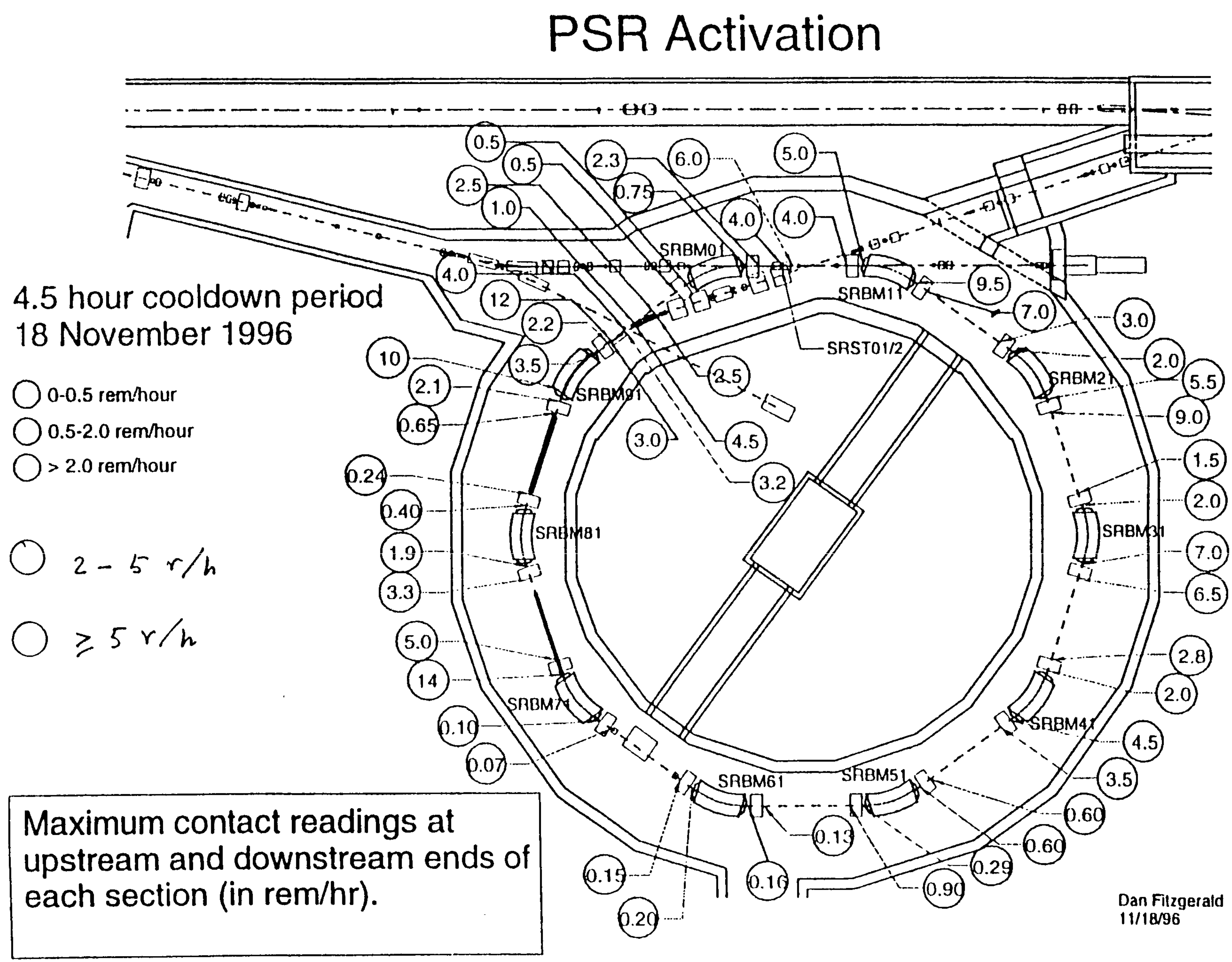


Figure 3. Late 1996 activation map.

Broad Band Impedance

	Z_ℓ/n	Z_T
Bellows	1.1	8.8
Vacuum ports	0.49	3.9
Valves	0.28	2.2
Steps	16.8	134.4
Collimator	1.04	8.3
Total	19.7	157.6
Unit	$j\Omega$	$jK\Omega/m$

- Dominated by steps.
- Moderate tapering and shielding are proposed.
- Compare with $j14\ \Omega$ for ISR, $j16\ \Omega$ for SPS, and $j30\ \Omega$ for AGS.
- **Do we need further reduction of this impedance?**
- **Sharp resonances for large steps, around 1 GHz.**

Narrow Band Impedance

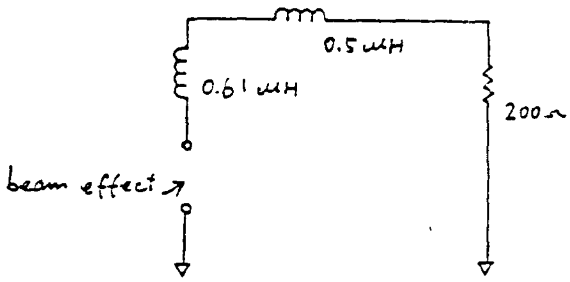
- RF cavity high order modes, large steps, other cavities in the chamber.
- **Consequences of the narrow band impedance for long bunches.**

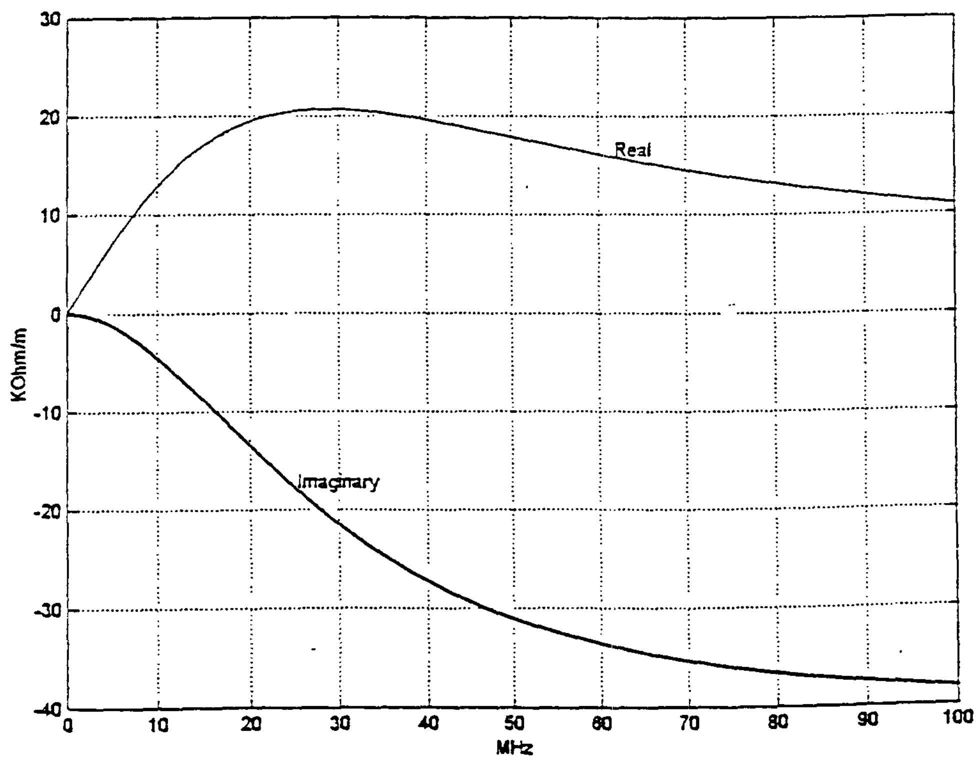
Extraction Kicker, Transverse

- 8 window frame magnet units, $\bar{\ell} = 40\ cm$, $2\bar{b} = 14\ cm$, all have height $2a = 11.5\ cm$.
- Conventional calculation, with 200 Ω charging resistance,

$$Z_T = \frac{c\omega\mu_0^2\ell^2}{4a^2 Z_k}\Omega/m$$

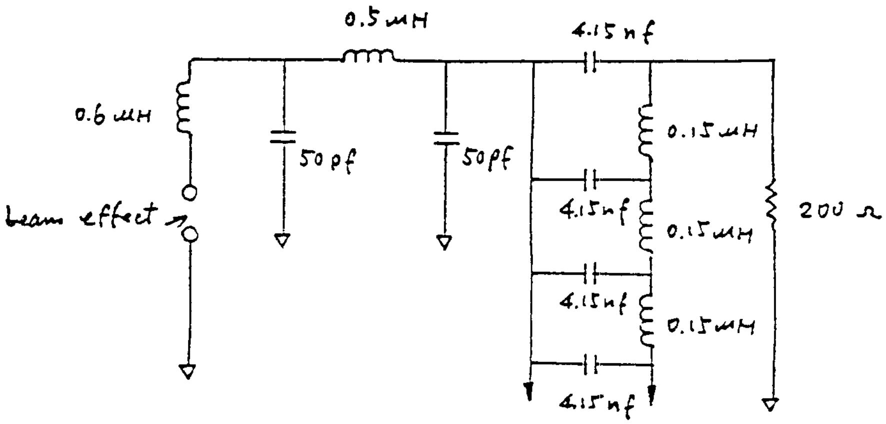
- $Z_{T,\mathrm{real}} \approx 20\ K\Omega/m$ at $30\ MHz$.

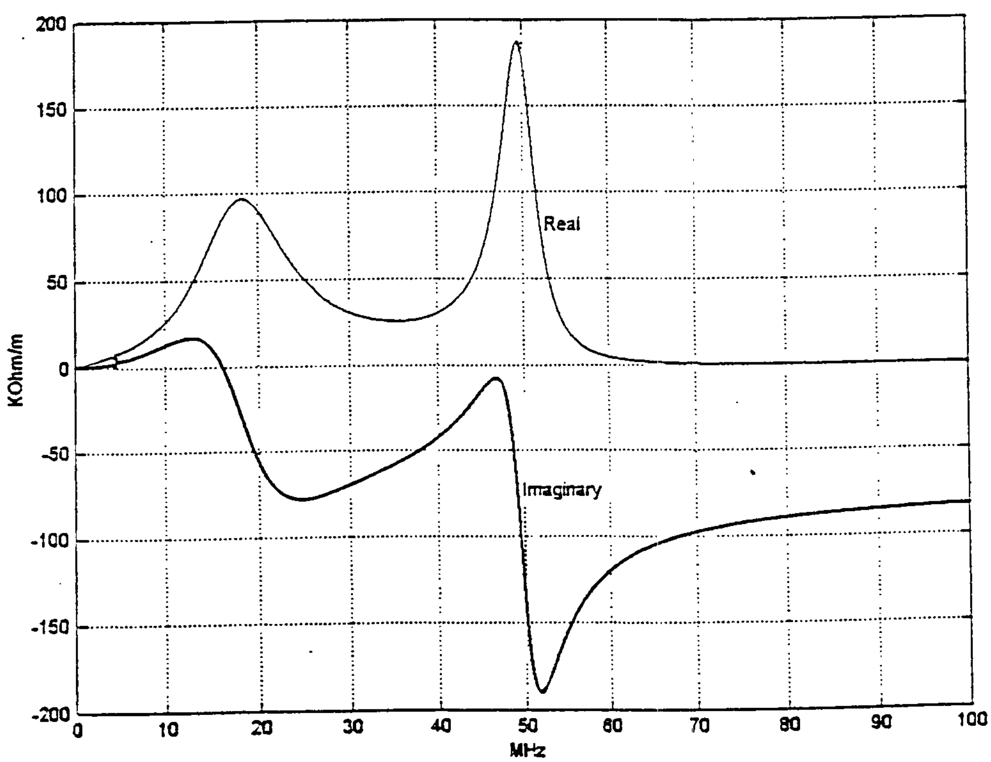




Extraction Kicker, Transverse

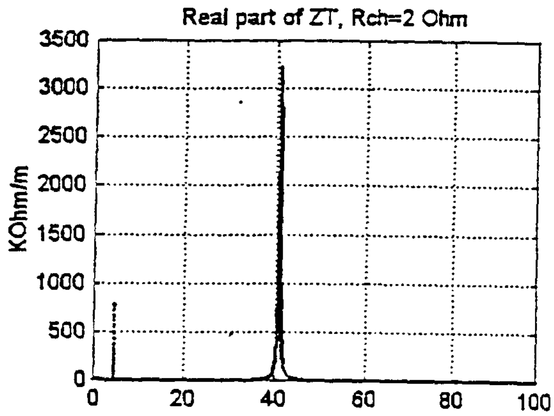
- More realistic termination with 50 pf capacitance around the stray inductance of 0.5 μH.
- This gives rise to $Z_{T,\text{real}} \approx 100\ K\Omega/m$ at 20 MHz, and $Z_{T,\text{real}} \approx 200\ K\Omega/m$ at 50 MHz.

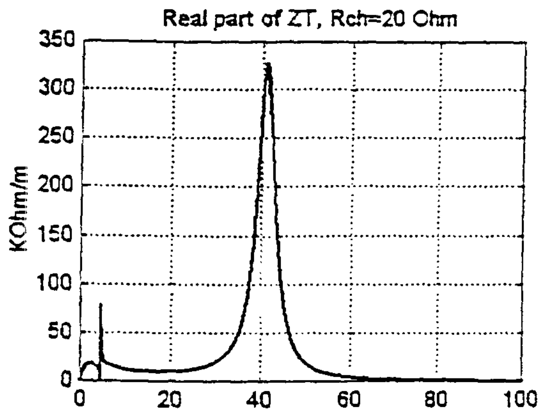


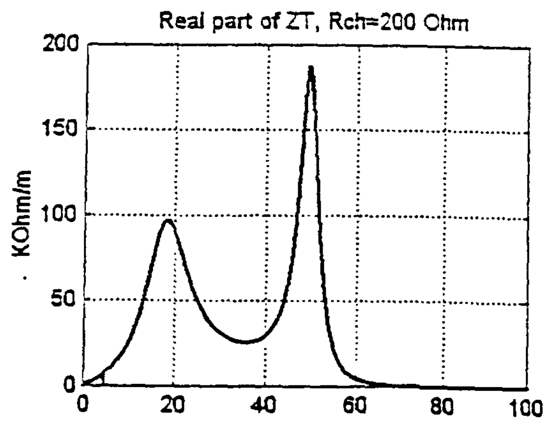


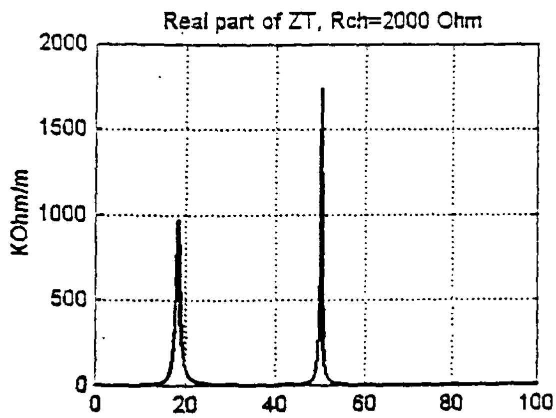
Extraction Kicker, Transverse

- Sensitivity to the termination.
- Example, just change the charging resistance as 2, 20, 200, 2000 Ω.
- Similar design for AGS and Booster. **No special care was needed. Why?**



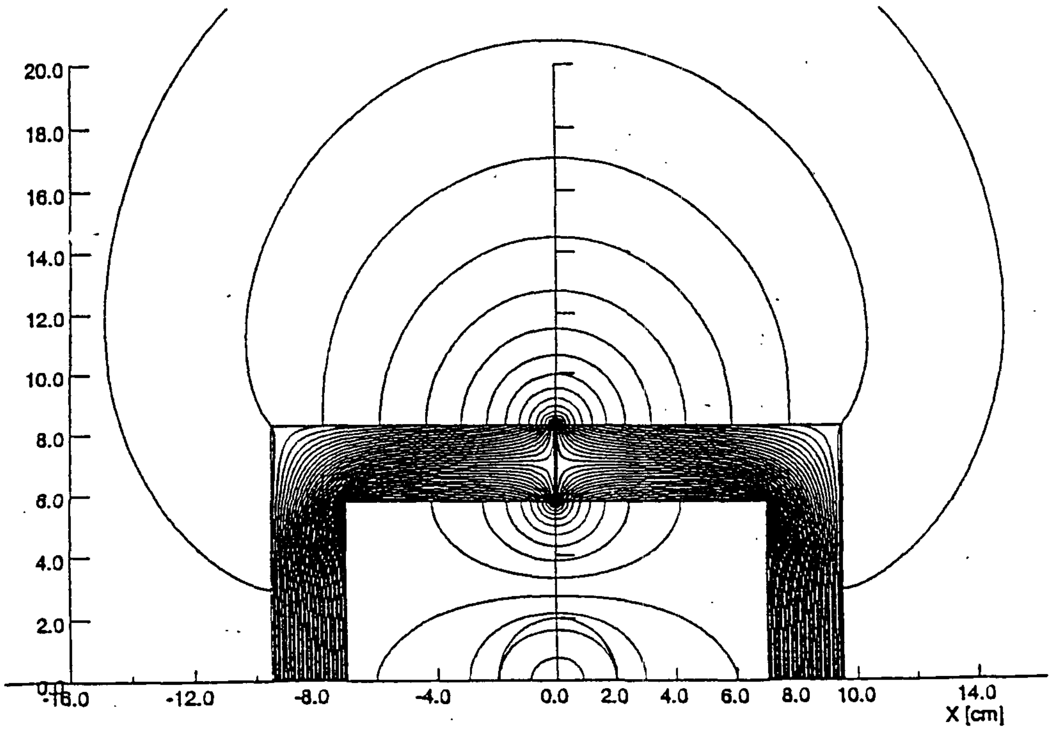






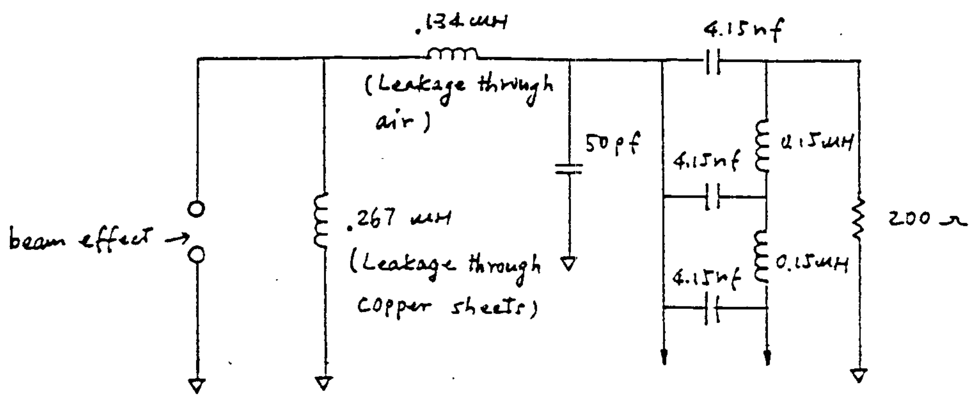
Extraction Kicker, Longitudinal

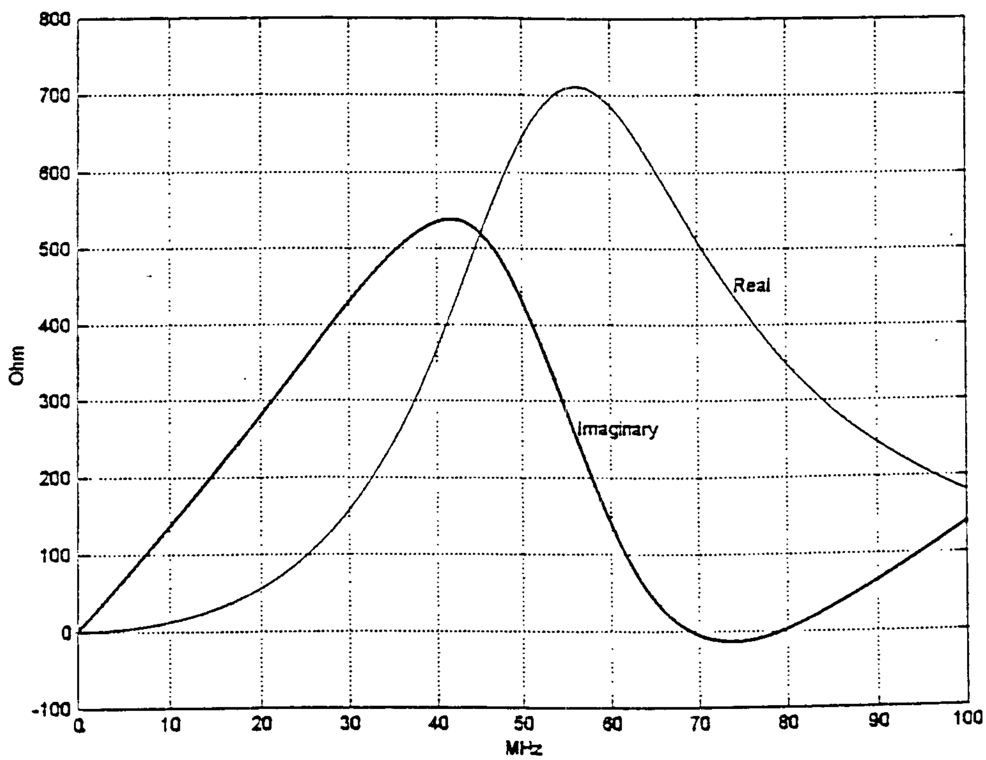
- Taking $\delta_{copper} = 1\ mm$, the total leakage inductance is $L_{leak} \approx 6\ \mu H$, which is equivalent to $Z_\ell/n = j45\ \Omega$.
- Present design of single power supply allows little image current on the conductors.
- Longitudinal space charge impedance is $Z_\ell/n = -j196\ \Omega$. The leakage may offset this impedance.
- **Longitudinal impedance compensation** using ferrite ring, at PSR, KEK PS, also proposed for proton driver at FNAL.



Extraction Kicker, Longitudinal

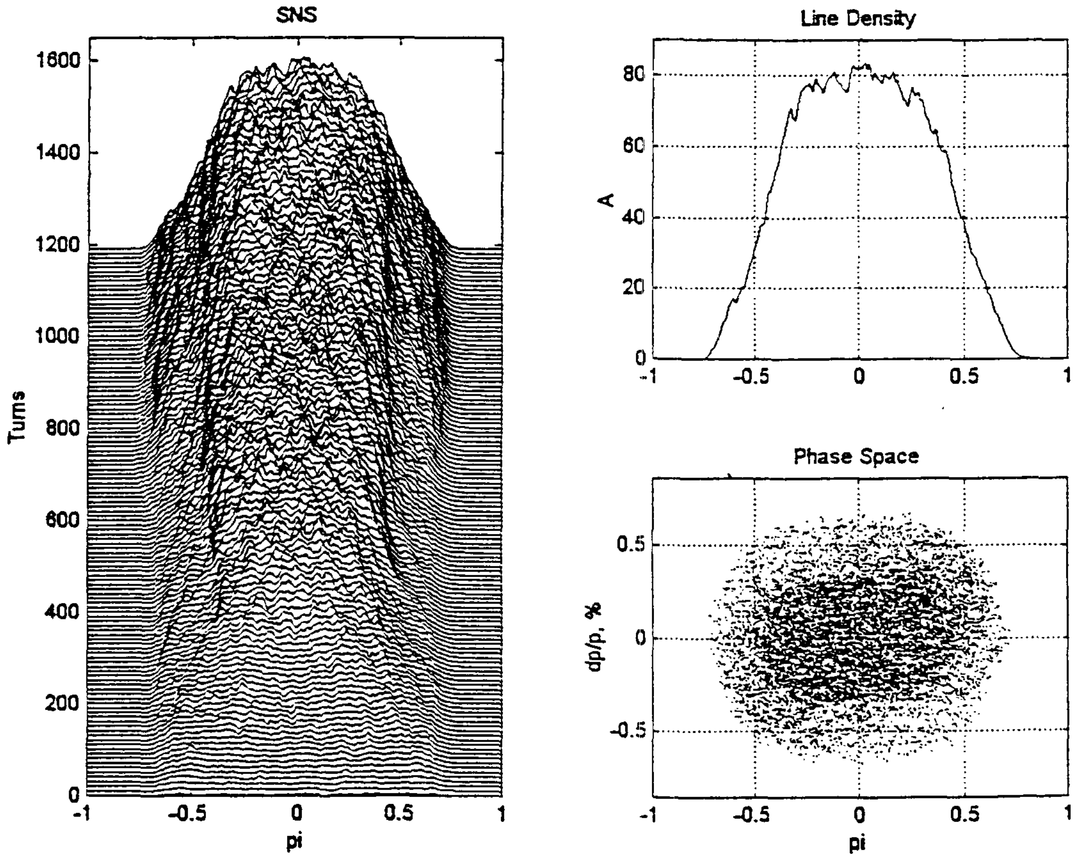
- Differential flux leakage through the gap air will couple the terminations, Voelker and Lambertson, 1989.
- Example. Let the gap air leakage be the half of L_{leak}, real part of impedance takes place around 60 MHz.
- **Extraction Kicker: impedance and engineering issues for window frame, C frame, travelling wave, and stripline type of kickers.**





Longitudinal Microwave Instability

- The Keil-Schnell criterion is satisfied if the beam $\Delta p/p \geq 0.65\%$. Below transition, the threshold is even higher.
- With RF voltage of 40 KV, the beam has $\Delta p/p = \pm 0.7\%$. By ramping the RF voltage from 20 KV to 40 KV at the end of stacking, we have $\Delta p/p = \pm 0.65\%$.
- ISIS experience showed that K-S criterion might be overestimated.
- To improve the beam momentum distribution in the ring, Linac beam $\Delta p/p = \pm 0.3\%$ is proposed. Beam loss might be a problem.
- **The effect of beam momentum distribution.**



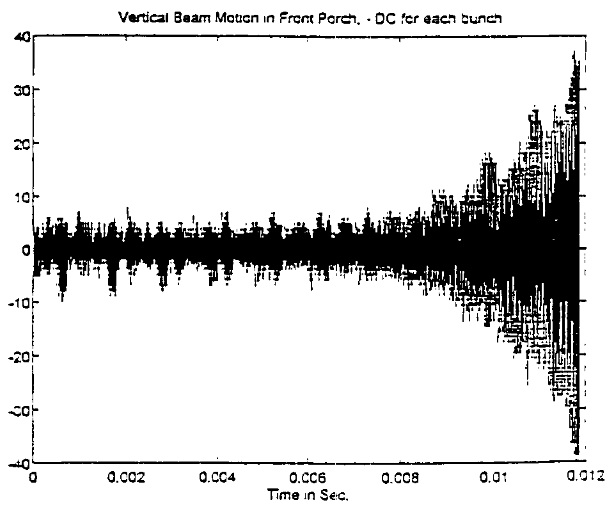
Resistive Wall Instability

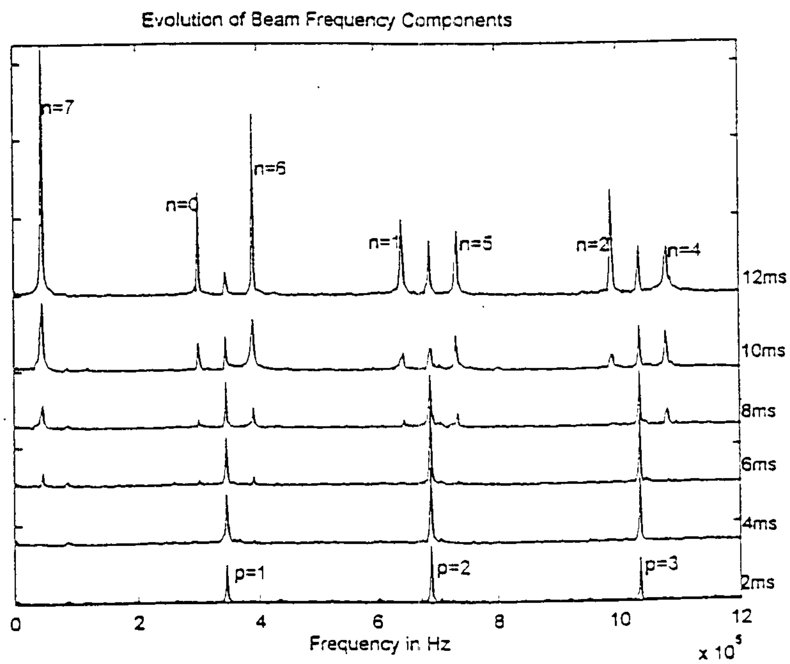
- The calculated growth rate is 1 ms at the end of stacking.
- Calculated AGS resistive wall instability growth rate is 0.37 ms, observed is 2 ms.
- Calculated Booster growth rate is 0.48 ms, but never observed the instability. Probably fast ramping helps to further damp the instability.
- Use of stainless steel for vacuum chamber is acceptable.

AGS

$\nu_y \doteq 8.85$

$N = 5 \times 10^{13}$ ppp





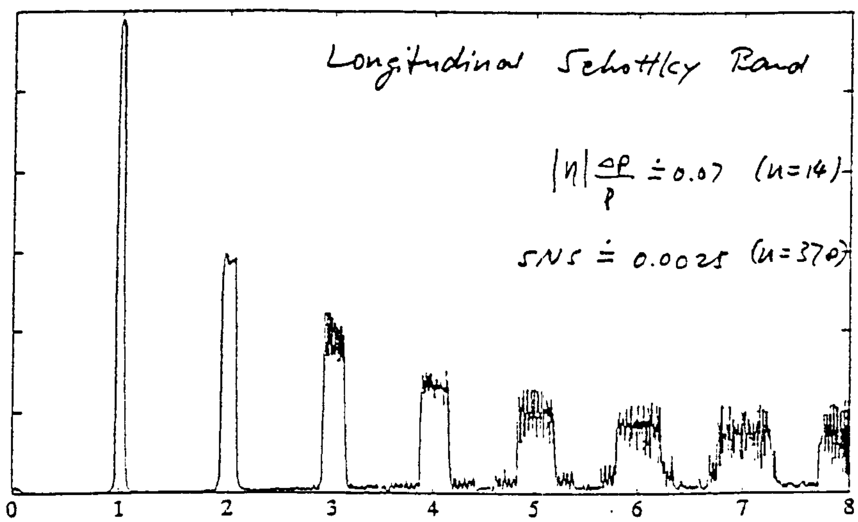
Transverse Microwave Instability

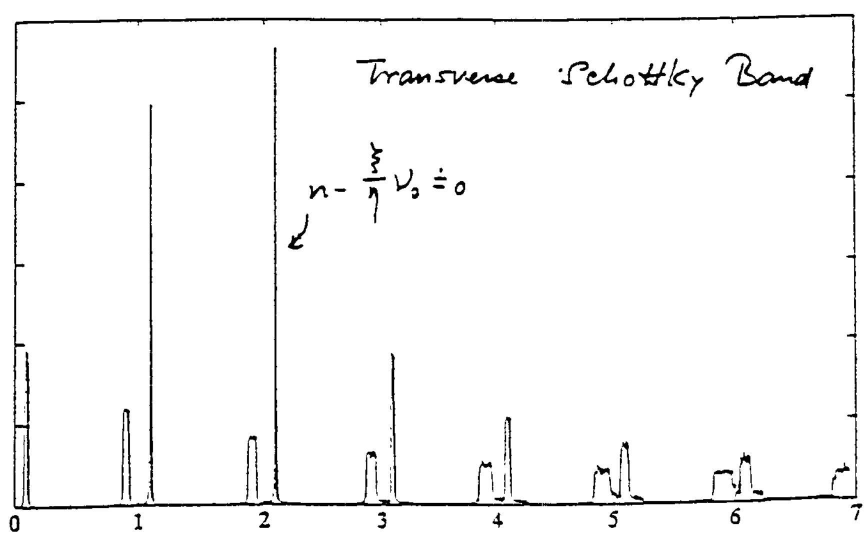
- LHC and RHIC have ~1 ns bunch, $W_{bh} \approx 2\ GHz$. The bunch length of SNS is 550 ns, giving rise to $W_{bh} \approx 3.6$ MHz.
- The transverse mode crossing may happen, but not the mode coupling.
- Entire beam life takes about a synchrotron period, conventional head-tail type instability will not be a serious problem.
- **Chromatic effect is complicated during the multi-turn injection.**
- **Transverse microwave instability may develop at a part of the beam, relevant to local peak current, associated impedance, and local coherent tune shift.**

Transverse Microwave Instability

- The damping due to the beam momentum spread is weak at the low frequency.
- For SNS, $\eta = -0.193$, $\Delta p/p = \pm 0.7\%$, the Schottky band overlaps at $n = 370$, i.e. 440 MHz.

Schottky Band, S.Y. Zhang and W.T. Weng, 1993





Transverse Microwave Instability, Coherent Tune

- Coherent tune shift is from the image effect and BB impedance,

$$\Delta\nu_{coh,wall} = \frac{-NRr_0}{2\pi\nu_0 B_f \beta^2\gamma^3 b^2}$$

$$\Delta\nu_{coh,BB} = \frac{j\beta e I_{peak}}{4\pi R m_0 \gamma\omega_\beta\omega_0} Z_{T,BB}$$

- At low energy, the coherent tune shift, is much larger than the combined tune spread of ξ, η, and synchrotron tune.

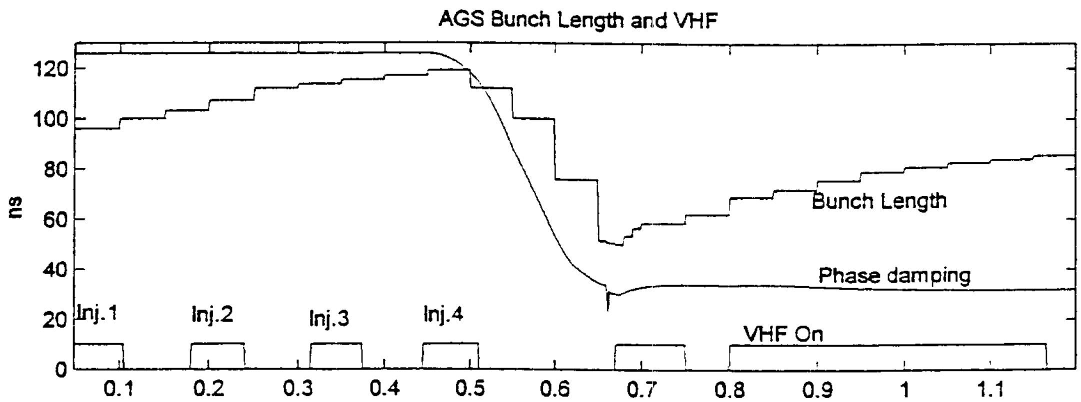
	AGS	PSR	Booster	ISIS	
N	6	3	2	4	10^{13}
B_f	0.3	0.4	0.4	1	
E_k	1.55	0.8	0.2	0.07	GeV
ξ	-0.2	-0.2	-0.2	-1.4	
dp/p	0.4	0.34	0.7	0.2	%
$\Delta\nu_{wall}$	1.77	0.77	5.63	10.9	%
$\Delta\nu_{BB}$	1.95	0.35	0.74	0.73	%
$\Delta\nu_{coh}$	**3.84**	**1.12**(1.5)	**6.37**	**11.6** (10)	%
$\|\xi\| \nu_0\Delta p/p$	0.71	0.14	0.69	1.09	%
$\eta\Delta p/p$	0.05	0.06	0.45	0.16	%
$\Delta\nu_S$	0.27	0.04	0.3	0	%
$\Delta\nu_{inc}$	**1.03**	**0.24**	**1.44**	**1.25**	%

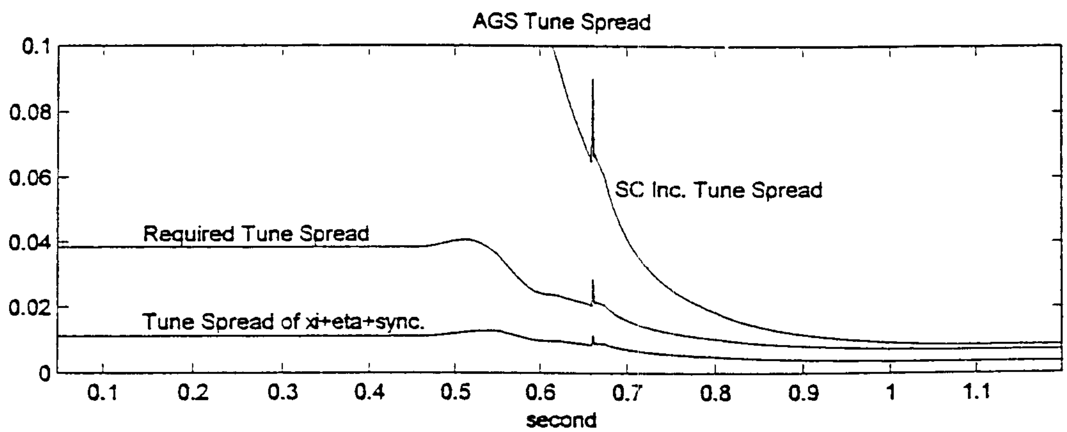
Transverse Microwave Instability, AGS

- AGS experience

  1. At low energy, below transition, beam is stable.
  2. Beam could be unstable in transverse at high energy. VHF dilution $\sim 200\ ms$ above transition, at $\sim 18\ GeV$.

- **Possible damping effect of space charge incoherent tune spread, which diminished at high energy.**

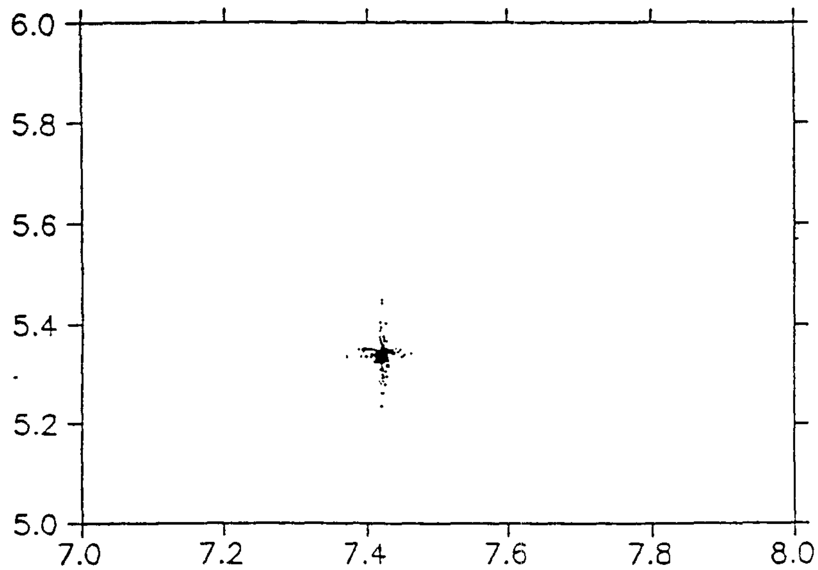




Transverse Microwave Instability, SC Effect

- Conventional work assumed uniform distribution, which generates incoherent tune shift, but little spread.
- Gaussian distribution yields large spread, which is also betatron amplitude dependent.
- In general, both image and BB coherent tune shifts go with the same direction of the incoherent tune shift.

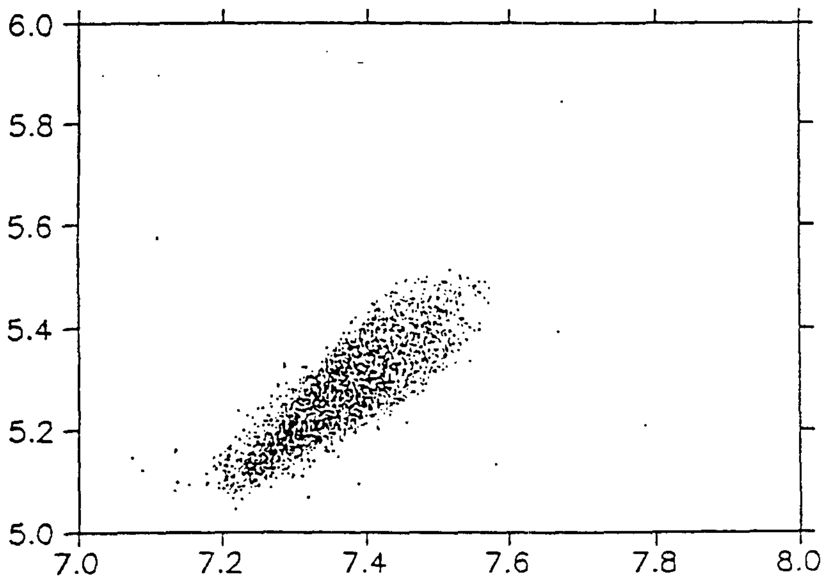
K-V



Yu. Senichev

1995

Gaussian



Same rms

Transverse Microwave Instability, SC Effect

- Complications.

    1. Analytical approach is difficult, because of the distribution in the tune diagram.
    2. Image coherent tune shift may go other way for non-circular chamber.
    3. BB impedance coherent tune shift may go other way for some chamber geometry, D'yachkov and Ruggiero, 1997.
    4. e-p type problem.

- Like other similar machines, conventional transverse microwave instability will not be a serious problem for the SNS.

- **Space charge effect in transverse microwave instabilities.**

- **Transverse space charge impedance issues.**

PSR Instability, Potential Well

- Potential well of SNS is about twice as high as PSR.

	PSR	SNS	SNS	
N	4	10.4	20.8	10^{13}
R	14.35	35.1	35.1	m
B_f	0.4	0.4	0.4	
b	5	10	10	cm
$a = \sqrt{2}\sigma$	1.2	2.4	2.4	cm
$V_{pot.}$	6	6.5	13	KV

- For e-p type instability, the space charge incoherent tune spread is not effective in damping.

  1. The electron induced proton beam coherent tune shift moves to other direction, out of the incoherent tune spread.
  2. If multipacting takes place, the neutralization factor could be large. At the SNS, $\eta_{neu} = 0.23$ could entirely offset the space charge effect, leading to zero tune spread (assume same distributions for e and p).

PSR Instability, $\Delta p/p$ Issue

- Numerous evidences showed that the beam $\Delta p/p$ is important in damping the e-p instability at PSR,

  1. Threshold is proportional to RF voltage V_{RF}. R. Macek: $N \propto n\ \Delta p/p \propto \sqrt{N}\sqrt{V_{RF}}$, therefore, $N \propto V_{RF}$. This is $N \propto (\Delta p/p)^2$.
  2. Instability improved by inserting ferrite rings, which cleared the gap, but also increased beam $\Delta p/p$.
  3. Coasting beam threshold increases with the larger Linac beam $\Delta p/p$.
  4. Chromatic effect is shown in the study, $\sim \Delta p/p$.
  5. Double RF study showed no change on the threshold. The peak current is reduced, but the beam $\Delta p/p$ also reduced, two effects may offset.
  6. Increasing the bare tune by one unit improves the instability. It was explained by the effect of $\xi\nu_0\Delta p/p$.

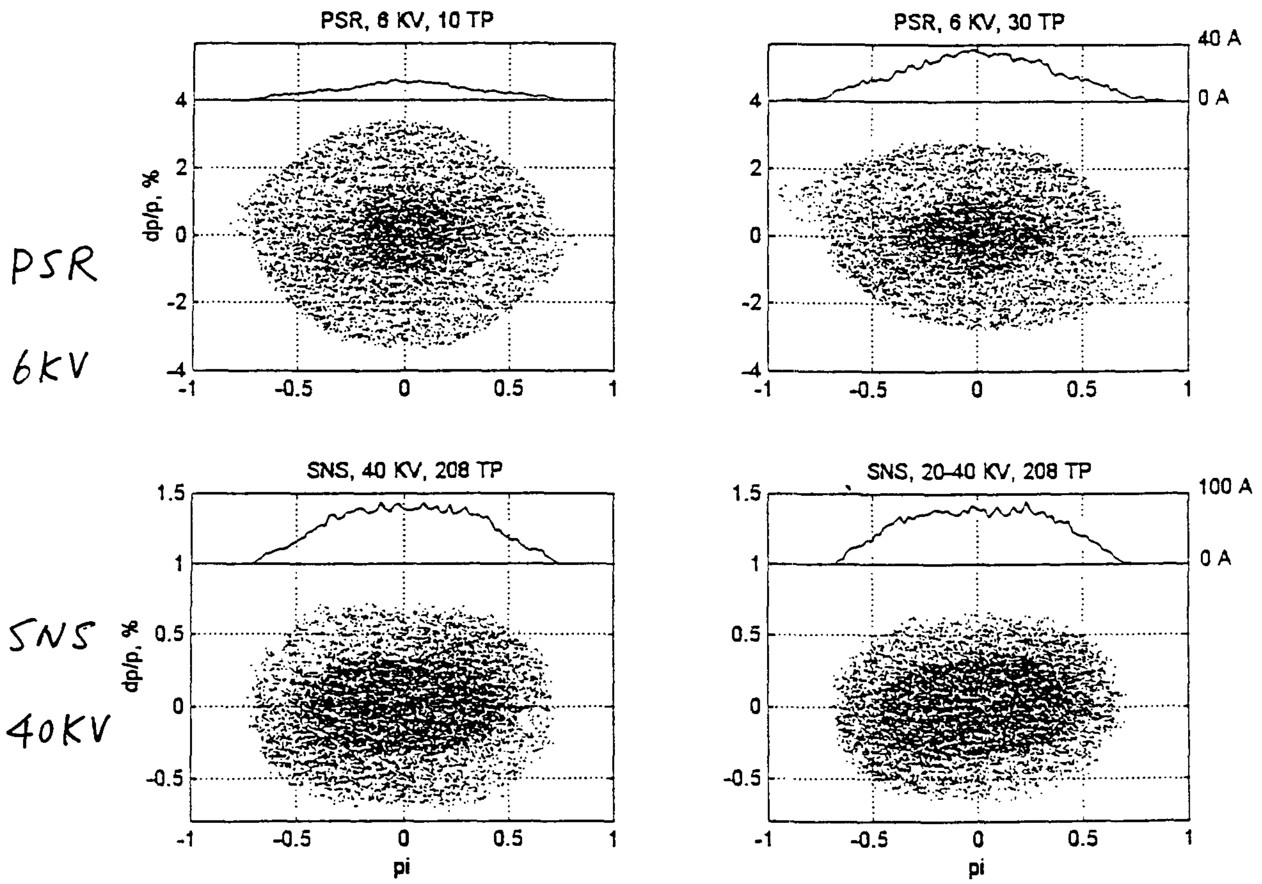
	PSR	SNS, 1MW	SNS, 2MW	
$\Delta p/p$	0.34	0.7	0.7	%
n	60	86	120	
η	-0.188	-0.193	-0.193	
$\Delta\nu = n\eta\Delta p/p$	3.8	11.6	16.2	%
$\Delta\nu/V_{pot.}$	0.63	1.78	1.25	

PSR Instability, Clean Gap

- Another important issue is the clean bunch gap

  1. 40 KV RF voltage at the SNS sufficiently suppresses the longitudinal space charge induced voltage of $\sim$15 KV.
  2. A gap cleaning kicker is proposed.
  3. **The effect of longitudinal impedance of the extraction kickers.**

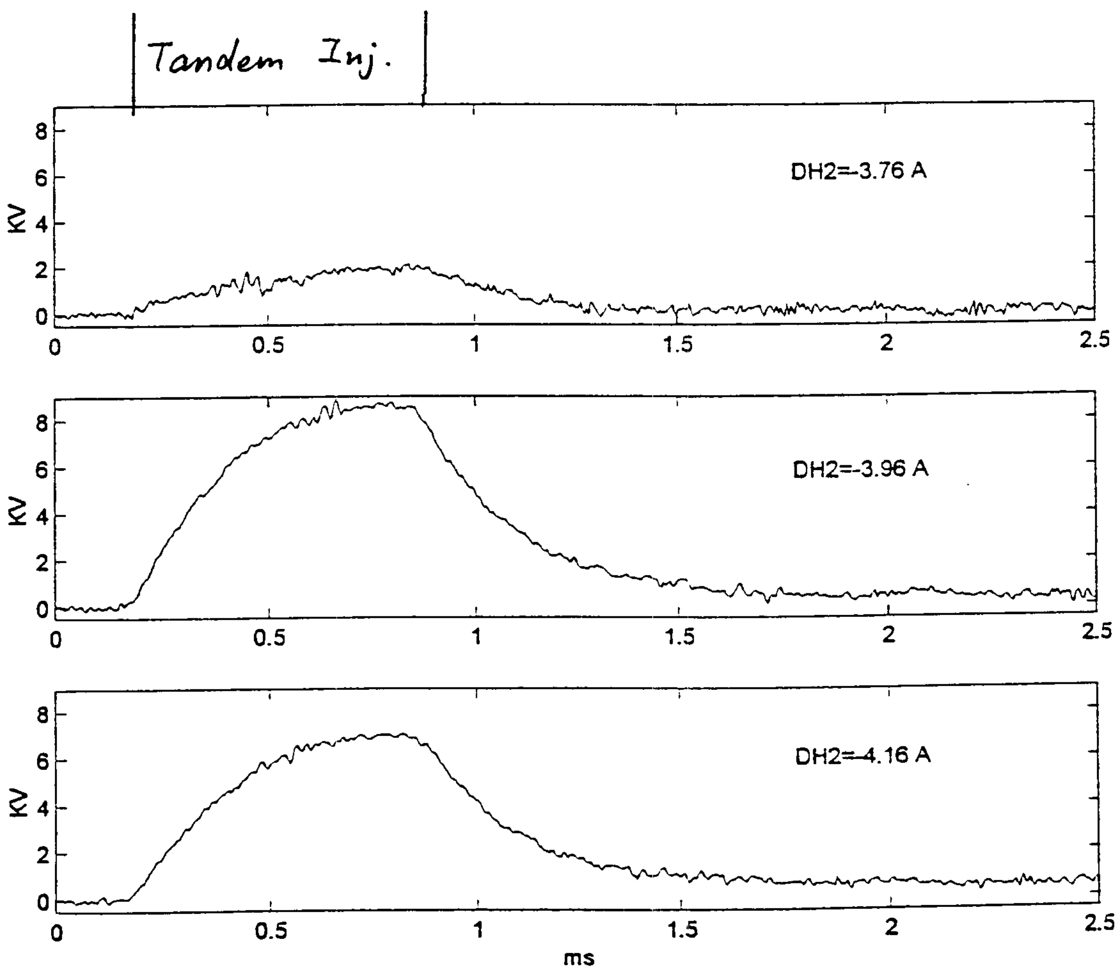
S.Y. Zhang and W.T. Weng, 1998



PSR Instability, Electron Production

- Booster study. Crashing 3×10^9 Au^{+31} particles into the injection septum, 8 KV voltage drop was observed. Translated equivalent SNS proton SE production rate was about 27.

Booster Injection Septum Voltage with Au^{31+} Beam Scraping, Different Angles.



PSR Instability, Electron Production

- Tandem study. P. Thieberger et. al. have shown the scraping effect of $\sin\theta^{-1.2}$.
- Multipacting, theory and experiment, M. Blaskiewicz.

Tandem Study

Scraping Effect in SE Production, with H^+, O^{8+}, and Au^{31+} ions, Normalized.